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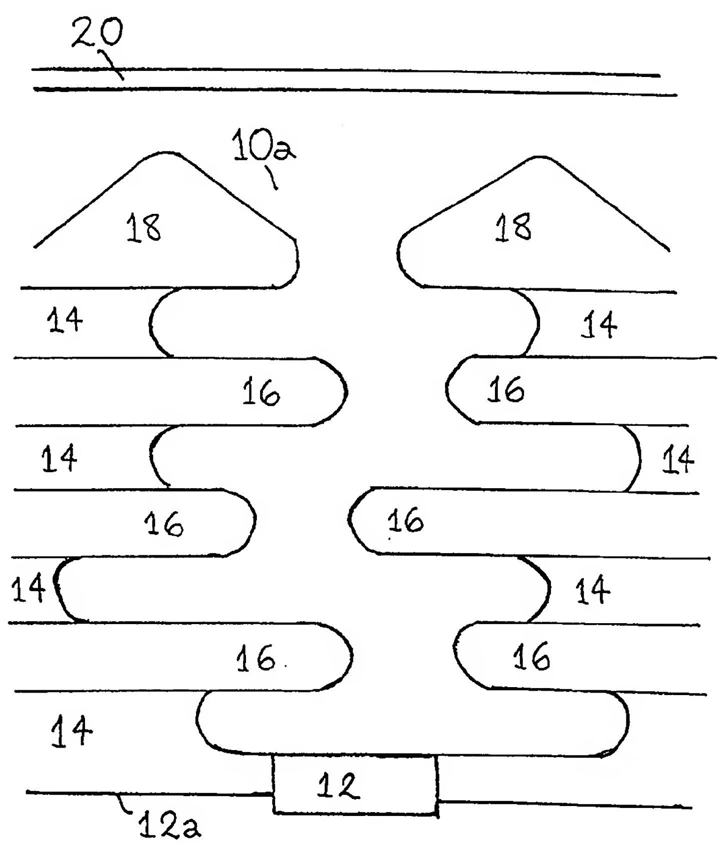
(57) Abstract

The electron multiplier array consists of alternate layers of metallic material (16) and insulator (14) deposited over an array of anodes (12) on a substrate. The layers are deposited in turn on the substrate and holes are etched through each of the layers to form an array of channels (10) over the array of anodes (12). The array repeat of the electron multiplier array is less than 0.5 mm and individual layers have a thickness of between 10 and 500 micron. This permits the fabrication of much smaller devices that are less susceptible to high magnetic fields.



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ELECTRON MULTIPLIER ARRAY

The present invention relates to an electron multiplier array and to a method of making the same.

Conventionally an electron multiplier, in the form of a photomultiplier tube for example, is constructed using a plurality of electrically conductive plates, each of which has high secondary electron emission characteristics. The conductive plates are individually mounted in a vacuum chamber in a column but physically separated from one another and with an anode at one end. The conductive plates are connected to a power source such that increasingly positive potentials are applied to successive plates in the column whereby free electrons are caused to accelerate towards the anode at the base of the column. When an electron is incident on the first plate in the column, distant from the anode, a plurality of electrons is produced by the plate because of its high secondary electron emission. The electrons produced by the first plate are accelerated towards the anode and in turn are incident on the next plate. Thus, ever increasing numbers of electrons are emitted by each of the plates as the electrons are accelerated towards the anode at the base of the column in a cascade.

In an article appearing in Nuclear Instruments and Methods in Physics Research A 343 (1994) 263-267 entitled Status of the Ceramic Multichannel PM Tube, G Comby et al, a photomultiplier array is described which is constructed from individual ceramic plates that are stacked alternately as dynode layers and insulation layers. A plurality of holes are drilled into each individual ceramic plate and the ceramic plates are stacked so that the holes in adjacent plates are in staggered alignment. The walls of the holes in the dynode plates are lined with a conductive material that is in electrical contact with an applied positive potential so that electrons in the channel defined by the holes are accelerated towards an anode at the base of the stack.

Conventional electron multiplier devices of the type described above, have the disadvantages that the devices are bulky and are susceptible to high magnetic fields which significantly reduces potential applications for such devices. Moreover, the method of making the devices is costly and time consuming. Each plate must be manufactured separately and when the plates are stacked care must be taken to ensure the necessary staggered alignment.

The present invention seeks to provide an electron multiplier array and a method of making the same that overcome at least in part some of the disadvantages of such conventional devices. In particular the present invention provides a method of making an electron multiplier array using micro-engineering techniques.

In a first aspect the present invention provides a method of fabricating an electron multiplier array comprising providing an array of anodes on a substrate, depositing alternate layers of a metallic material and an insulator on the substrate in the form of a stack and etching through each of the layers to form an array of substantially parallel channels over the array of anodes.

With the present invention, individual plates are not separately fabricated and subsequently stacked together. Instead, the layers are built up from a substrate using conventional deposition and etching techniques. This enables the electron multiplier array to be fabricated considerably smaller than existing electron multipliers and much more cheaply.

Each of the layers of metallic material is connected to a separate voltage potential with the voltage potential varying with respect to the position of the layer of metallic material in the stack.

Preferably, after each layer is deposited an array of holes is etched through the layer and the holes are filled with resist before the next layer is deposited and wherein the resist in the holes is removed only after the holes in the uppermost layer of the electron multiplier have been etched

thereby forming the array of channels.

More preferably, the holes in each layer of metallic material are positioned so as to only partially overlap the holes in the preceding layer of metallic material and ideally, the holes in each of the layers of insulator are etched so as to expose a portion of the upper surfaces of the respective layers of metallic material immediately beneath.

Ideally, the channels in each layer are etched in a hexagonal array.

Furthermore, a photosensitive layer may be deposited on the uppermost metallic layer to form a photomultiplier.

In a second aspect the present invention provides an electron multiplier array comprising a plurality of alternately stacked layers of a metallic material and an insulator having an array of channels extending through the layers of metallic material and insulator, each of the channels being closed at one end by a respective anode and each of the metallic layers having a connection for application of a voltage potential which varies with respect to the location of the metallic layer within the stack characterised in that the array is provided on a substrate and has a array repeat of less than 0 5 mm.

With the present invention, a large array is provided of parallel identical miniature electron multiplier structures having stacked annular dynodes which by virtue of their small size are much less susceptible to high magnetic fields and so are suitable for use in circumstances where such magnetic fields are present. Moreover, the array may be put to use to good effect as an image intensifier as the pixel resolution is smaller than normal visible acuity and is capable of detecting single photons.

An embodiment of the present invention will now be described by way of example only with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of a cross-section of one photomultiplier of an array of photomultipliers fabricated in accordance with

the present invention;

Figure 2 shows the surface structure of an array of photomultipliers fabricated in accordance with the present invention, and

Figure 3 is a schematic diagram of an array of interconnected dynodes illustrating how current flows outwardly from a shorted photomultiplier channel.

A photomultiplier array having the structure shown in the accompanying Figures is fabricated using micro-engineering techniques. Firstly, a thin layer of a first metallic material having a low secondary emission coefficient, for example gold, is deposited on a substrate using conventional techniques. The first metallic layer is then etched using conventional techniques to form a network of thin strips of the metallic material which interconnect at nodes in a regular grid structure with a spacing of between 10 and 500 microns, preferably less than 100 microns. A thick layer of silicon dioxide is deposited over the substrate and the nodes and a mask is then used to etch away the silicon dioxide to form an array of apertures or holes, having a diameter of between 5 and 50 microns, each located above and exposing one of the nodes. The same metallic material is then deposited in each of the apertures to form an array of interconnected anodes 12 and the anodes 12 and insulation 14 are planarised.

A new layer 14 of silicon dioxide is then deposited over the existing silicon dioxide layer and the anodes 12. Over the top of the new layer of silicon dioxide a layer of a second metallic material 16 is deposited which has a high secondary electron coefficient, for example Ag.MgO. An array of holes is etched into the layer of metallic material using the mask. The array of holes is offset from the array of anodes 12 beneath such that a portion of the rims of the metallic layer that define the etched holes partly overlie the anodes but do not wholly obscure the anodes. A 1:1 wet etch is then performed to etch the silicon dioxide beneath the layer of metallic

material to expose each of the anodes 12 and to form an array of channels 10 from the holes in the metallic layer to the anodes. The silicon dioxide is further etched back to partially expose the lower surfaces of the rim regions of the metallic material about the holes. Resist is then deposited in the channels 10 as far as the upper surface of the metallic layer.

A further layer of silicon dioxide is then deposited over the metallic layer and the resist followed by a further layer of the second metallic material using conventional techniques. The mask is again used to etch an array of holes in the new metallic layer. With this new metallic layer the mask is offset in the opposite direction to that of the lower metallic layer so that the portions of the rims of the new metallic layer that partly overlie the anodes are opposite to the overlying rim portions in the lower metallic layer. The silicon dioxide immediately below the array of holes in the new metallic layer is etched away as far as the resist to continue the channels 10. The silicon dioxide is further etched to undercut and expose the lower surfaces of the rim regions of the new metallic layer and the upper surfaces of the rim regions of the lower metallic layer. Resist is again deposited in the channels as far as the upper surface of the new metallic layer.

The method is cyclically repeat for additional layers of silicon dioxide and metallic material with, in each case, the etched array of holes in the metallic layer being offset from the array of holes in the previous metallic layer until the desired number of metallic layers, which thereby form the individual dynodes, have been deposited. The uppermost layer of the stacked structure is formed from a layer of the second metallic material. The resist in the channels 10 is then removed using conventional techniques to produce open channels extending from the uppermost metallic layer to the anodes 12.

The thickness of the individual layers is around 1-10 microns and is related to the diameter of the channels 10. A negative resist is employed to dry etch into the upper metallic layer 18 an array of generally conical

channels each having an upper hexagonal profile. The conical channels are each aligned, using fiducial markers, with a respective anode 12. Each of the channels has a diameter of between 5 and 50 microns.

The edges of the metallic layers may also be etched sufficiently to ensure the rims of the metallic layers are rounded off. However, although some variation in the diameter of the holes between the upper surface and the lower surface of the metallic layers may occur, the diameter of the holes at the upper surface and the diameter of the holes at the lower surface are substantially the same. Finally, any necessary additional treatments are performed such as baking in an oxygen atmosphere.

A photosensitive material is then deposited using conventional evaporation techniques over the uppermost metallic layer to form the photocathode. The photosensitive material is prevented from entering any of the channels 10 by off-setting the source and rotating the array under fabrication. Finally, the electrical connections to the anodes and each of the dynode layers are formed and the entire structure is sealed in a steel or glass package under vacuum. The overall thickness of the device is thus only a few millimeters with the majority being as a result of the packaging rather than the device itself.

The structure of a single photomultiplier is shown in Figures 1 and 2. The photomultiplier comprises a channel 10 that is closed at one end by an anode 12 and is open at its end distant from the anode 12. The wall of the channel 10 is defined by the exposed edges or rims of alternate layers of insulation 14 and dynodes 16. The photomultiplier includes a plurality of dynodes; three are shown in Figure 1. An upper photosensitive layer 18, adjacent the opening to the channel 10, forms the photocathode of the photomultiplier structure. The array of photomultiplier structures are sealed in a high-vacuum package with a quartz or glass window 20 over the openings to the channels.

In cross-section the channel 10 is generally circular. The diameter

of the channel 10 though will vary with respect to the depth of the channel. Each of the insulating layers 14 is etched back so that the edge regions of the dynodes 16 project into the channel 10 beyond the edge regions of the insulation layers 14. In addition, the surfaces of the edge regions of the dynodes 16 are smoothly curved to minimise the presence of sharp or pointed edges. The channel 10 is substantially vertical but follows a repeating doubled curve path as each dynode is offset from the dynode below and the dynode above.

The photocathode 18 is shaped so that the upper open end of the channel 10a is wider than the average diameter of the channel 10 and is hexagonal, as seen more clearly in Figure 2. From the upper open end 10a of the channel, the channel funnels down to and merges with its diameter as defined by the edges of the dynodes 16. As the upper surface of the photocathode describes a tightly packed hexagonal 'honeycomb' structure, all the upper surface of the photocathode is therefore electrostatically connected to one or other of the insulator/metallic stacks thereby maximising the collection of incident electrons.

The anode 12 is shaped so that it is generally circular in cross-section and preferably has a diameter substantially corresponding to the diameter of the apertures in the dynodes 16. The anodes of each of the channels in the array are connected together by thin metallic strips or wires 12a. In addition, at the edge of the array (not shown) electrical connections are provided to each of the dynodes 16 and the photocathode 18 in order that an increasing positive voltage potential may be applied.

Whilst only three dynode layers are shown in Figure 1, alternative numbers of layers may be employed depending upon the operating parameters of the photomultiplier array. However, the number of dynode layers must be sufficient to overcome the front-end noise and the addition of more layers than necessary should be avoided as each extra layer introduces difficulties in fabrication and increases the danger of

breakdown.

With the photomultiplier array described above the uppermost metallic layer 18 is coated to act as the photocathode. Alternatively, the uppermost metallic layer may function simply as the first dynode in the stack of dynodes, in which case the window 20 may be coated with a photosensitive material so as to function as the photocathode.

In use, positive voltage potentials are separately applied to each of the dynode layers 16. The potentials are increased the nearer the dynode layers are to the anode 12 in steps of around 100-500 volts (assuming between 6 and 10 secondary electrons). In addition, the window 20 has a slightly negative potential applied with respect to the potential of the cathode 18. Incident photons pass through the window 20, strike the photocathode 18 and cause electrons to be emitted that are accelerated towards the anode 12. At least some of the free electrons strike the exposed surfaces of the dynodes 16 causing additional electrons to be ejected, in a cascade effect, which are also accelerated towards the anode 12. The electrons incident on the anode 12 cause a change in the current through the anode that is sensed indicating detection of an incident photon.

The etching back of the insulation layers 14 acts to prevent or at least reduce the effect of any charge electrostatically adhering to the edges of the insulator which might otherwise affect the electric field between adjacent dynodes 16. Also, the smoothly curved surfaces of the dynodes 16 reduce the possibility of high field regions being formed that might produce field emission and breakdown. Furthermore, as the anodes 12 have a diameter substantially equal to the diameter of the dynodes 16 and are connected by only thin strips, any stray capacitance to earth can be minimised which improves the signal-to-noise ratio as well as the electrical speed of the array.

The photomultiplier array is capable of detecting single photons with

an efficiency comparable to conventional photomultiplier tubes. Furthermore, the rise time of the device is very fast and the array is tolerant of high magnetic fields.

Although reference has been made to the insulation layers 14 consisting of silicon dioxide, other insulators such as spun polyamide may alternatively be employed as appropriate. As mentioned above, the dynodes 16 are fabricated from a material having a high secondary emission coefficient. Suitable materials are already in use in conventional photomultiplier tubes such as Ag.MgO, CuBeO and Ni.Al_2O_3, the oxides being surface formed. The anode, on the other hand, is a metallic material having a low secondary emission coefficient. Suitable materials include gold or platinum plating and cadmium. The photomultiplier array is sealed in a high-vacuum package preferably fabricated from stainless steel or metallised glass (suitably gettered). The window 20, which is of quartz or glass, is backed with indium-tin-oxide (ITO) so that a potential may be applied to the window without affecting its transparency. The ITO layer may be kept thin as it acts simply as a collector of stray ions and also acts to improve the photo-electron efficiency of the array.

The electron multiplier array described above may have a surface area of many square centimeters in which thousands of individual electron multipliers are formed. This means that for some applications many of the individual channels are redundant and failure of a few of the individual channels in the array need not undermine the overall performance or effectiveness of the device, as long as failure of individual channels does not result in failure of the whole array. Such failures may result during fabrication or as a result of a foreign particle entering a channel. To address this problem, the metallic layers that form the dynodes may be etched after each is deposited to form dynode rings instead of holes in an otherwise continuous sheet of the metallic material. Each dynode ring is fabricated so that it surrounds a channel and is connected by thin strips or

wires of the same material to each of its nearest neighbours, which will be six for the hexagonal structure described above and eighteen to its next nearest neighbours. Referring now to Figure 3, if one of the photomultipler channels 110 is shorted, then the maximum current will flow through the six wires 121-126 connecting the dynode surrounding the shorted channel whilst only one third of that current will flow in the next zone via wires 131-148. By appropriate selection of the current the six connections to a dynode surrounding a shorted channel can be fused without causing damage to the connections to the dynodes of the remaining channels (within a 3:1 safety factor). In this way a completely automatic system is provided for disabling and isolating damaged channels to permit continued use of the photomultiplier array by selection of the supply current to match the fusing limit of the connections.

The large number of individual channels and the very small size of the channels means that the array is able to tolerate much higher magnetic fields than conventional devices by virtue of the reduction in the dimensions of the individual electron multipliers. Moreover, the array is resistant to ionising radiations and temperature variations that undermine conventional semiconductor devices. The electron multiplier array is therefore suitable for electro-magnetic and hadron calorimetry in particle physics experiments.

Whilst the above embodiment describes a photomultiplier, the electron multiplier may be employed in various alternative devices. For example, the anode may be replaced by a phosphor screen to thereby provide an image intensifier which is not only very thin but also has an extremely small pixel size and thus excellent resolution. Of course further applications for the electron multiplier array will be immediately apparent.

CLAIMS

1. A method of fabricating an electron multiplier array comprising providing an array of anodes on a substrate, depositing alternate layers of a metallic material and an insulator on the substrate in the form of a stack and etching through each of the layers to form an array of substantially parallel channels over the array of anodes.

2. A method as claimed in claim 1, wherein each of the layers of metallic material is connected to a separate voltage potential with the voltage potential varying with respect to the position of the layer of metallic material in the stack.

3. A method as claimed in either of claims 1 or 2, wherein after each layer is deposited an array of holes is etched through the layer and the holes are filled with resist before the next layer is deposited and wherein the resist in the holes is removed only after the holes in the uppermost layer of the electron multiplier have been etched thereby forming the array of channels.

4. A method as claimed in any one of the preceding claims, wherein the holes in each layer of metallic material are positioned so as to only partially overlap the holes in the preceding layer of metallic material.

5. A method as claimed in any one of the preceding claims, wherein the holes in each of the layers of insulator are etched so as to expose a portion of the upper surfaces of the respective layers of metallic material immediately beneath.

6. A method as claimed in any one of the preceding claims, wherein the

channels are etched in a hexagonal array.

7. A method as claimed in any one of the preceding claims, wherein a photosensitive layer is deposited on the uppermost metallic layer to form a photomultiplier.

8. An electron multiplier array comprising a plurality of alternately stacked layers of a metallic material and an insulator having an array of channels extending through the layers of metallic material and insulator, each of the channels being closed at one end by a respective anode and each of the metallic layers having a connection for application of a voltage potential which varies with respect to the location of the metallic layer within the stack characterised in that the array is provided on a substrate and has a array repeat of less than 0 5 mm.

9. An electron multiplier array as claimed in claim 8, wherein silicon dioxide is used to form the layers of insulation.

10. An electron multiplier array as claimed in claim 8, wherein polyamide is used to form the layers of insulation.

11. An electron multiplier array as claimed in any one of claims 8 to 10, wherein the metallic material is selected from one of the following: Ag.MgO, CuBeO and $Ni.Al_2O_3$.

12. An electron multiplier array as claimed in any one of claims 8 to 11, wherein the channels are formed from holes in each layer and the holes in the layers of metallic material are positioned so as to only partially overlap the holes in the preceding layer of metallic material.

13. An electron multiplier array as claimed in any one of claims 8 to 12, wherein a portion of the upper and lower surfaces of each layer of metallic material surrounding the channels is exposed.

14. An electron multiplier array as claimed in any one of claims 8 to 13, wherein the thickness of any layer of metallic material or insulator is less than or equal to 100 microns.

15. A photomultiplier array consisting of an electron multiplier array as claimed in any one of claims 8 to 14 including a photosensitive layer on the uppermost layer of metallic material.

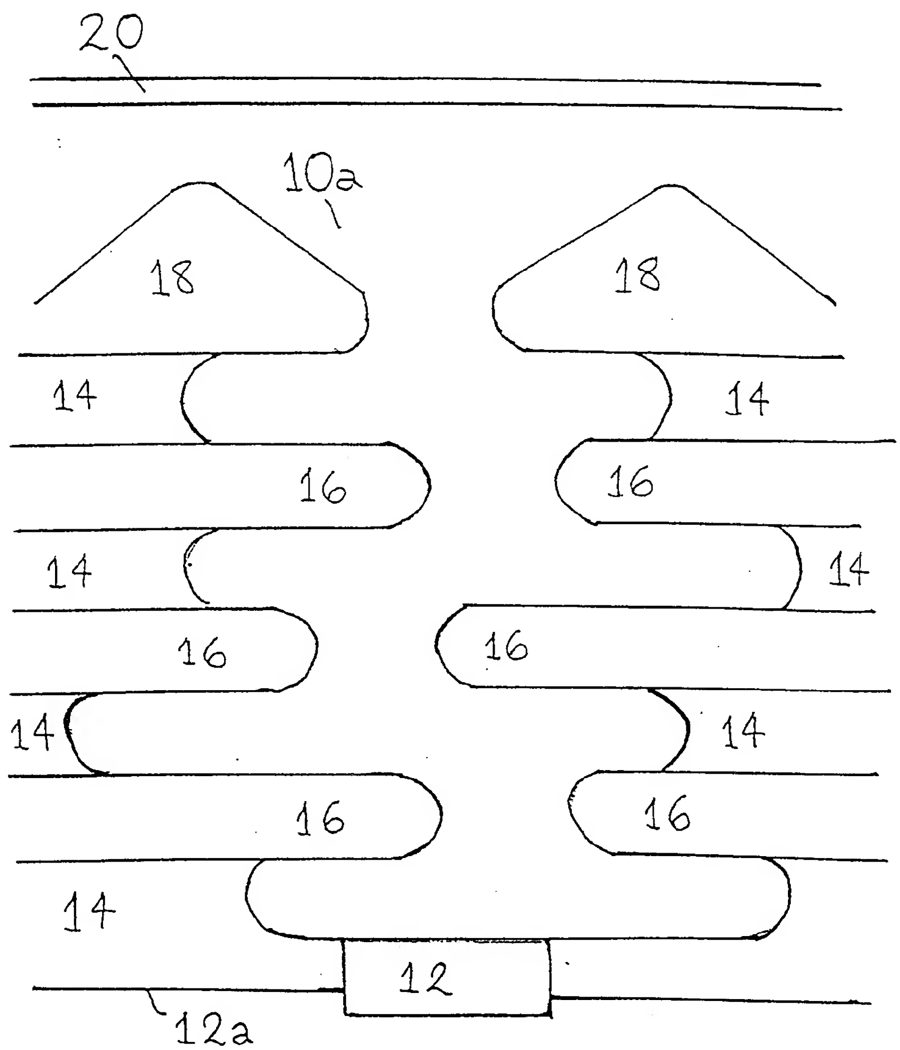

Figure 1

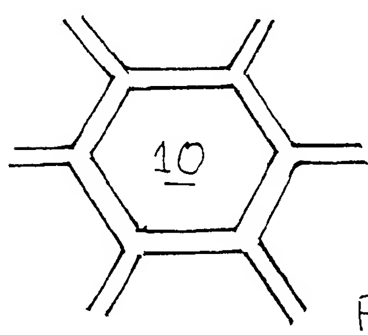

Figure 2

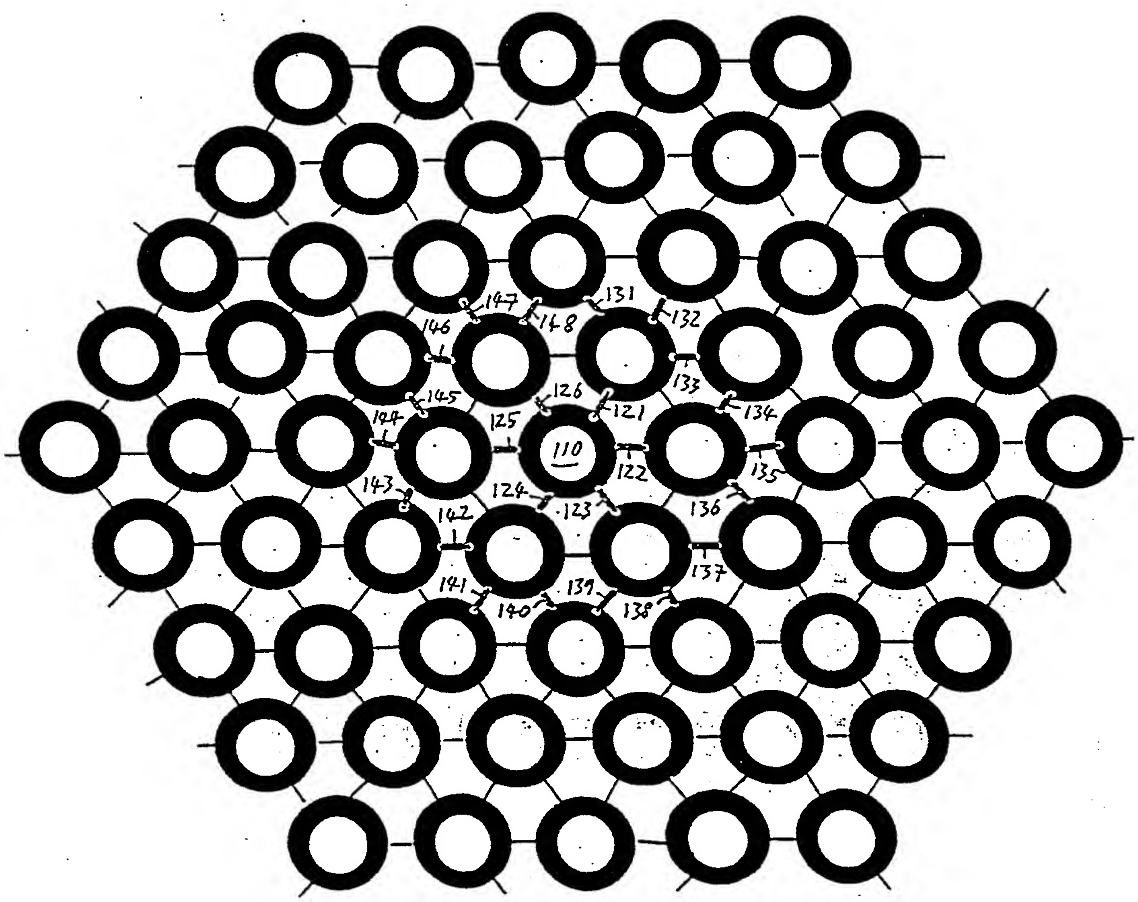
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Figure 3

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 98/02447

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01J9/12 H01J43/22

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A X	US 4 563 251 A (BECKER ERWIN ET AL) 7 January 1986 see column 4, line 49 - column 5, line 40; figures	1,2,4,5,7 8,12,14
A	EP 0 515 261 A (COMMISSARIAT ENERGIE ATOMIQUE) 25 November 1992 see column 7, line 30 - column 10, line 39; figures	1,8
A	WO 97 05640 A (CENTER FOR ADVANCED FIBEROPTIC) 13 February 1997 see abstract; figures	1,8

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
25 November 1998	09/12/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Schaub, G

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Inter. nal Application No
PCT/GB 98/02447

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	COMBY G ET AL: "Status of the ceramic multichannel PM tube" EXPERIMENTAL TECHNIQUES OF CHERENKOV LIGHT IMAGING. FIRST WORKSHOP ON RING IMAGING CHERENKOV DETECTORS, BARI, ITALY, 2-5 JUNE 1993, vol. 343, no. 1, pages 263-267, XP002085756 ISSN 0168-9002, Nuclear Instruments & Methods in Physics Research, Section A (Accelerators, Spectrometers, Detectors and Associated Equipment), 1 April 1994, Netherlands cited in the application see page 263, left-hand column, paragraph 2 - page 264, right-hand column, paragraph 1; figures 1,2	1,8

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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